MATCHED FILTER ENHANCED FIBER-BASED LIDAR FOR EARTH, WEATHER AND EXPLORATION

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Engineered for life

Modulated CW Laser Sources

- Continuous wave (CW) laser sources, such as those used in the telecommunication industry, are suitable for NASA missions.
- We have shown that by modulating these sources, and using phase sensitive detection or a matched filter receiver, very sensitive lidar systems can be constructed, using low cost and readily available fiber amplifiers/lasers.
- The compelling reason to use CW fiber sources is that the tremendous demand for products imposed on telecom industry has forced them to mature the technology and more critically the manufacturing processes to a very high level.
- The sustained market base ensures that they can routinely deliver a highly reliable product, at a low cost, in a timely manner. [These mission enabling criteria are difficult to meet by any one-off laser manufactured by industry or the government.]
- Exploit these lasers by impressing a modulated signal on the CW carrier
  - Sinusoidal
  - Pseudo-Noise (PN) code

Exploitation Of Lock-in Amplifier Technique [1]

- ***"Lock-in amplifiers are used to detect and measure very small AC signals all the way down to a few nanovolts.***
- ***<u>Accurate measurements may be made even when the small signal is obscured by noise sources many thousands of times larger</u>.***
- ***Lock-in amplifiers use a technique known as phase-sensitive detection to single out the component of the signal at a specific reference frequency and phase.***
- ***Noise signals, at frequencies other than the reference frequency, are rejected and do not affect the measurement."***

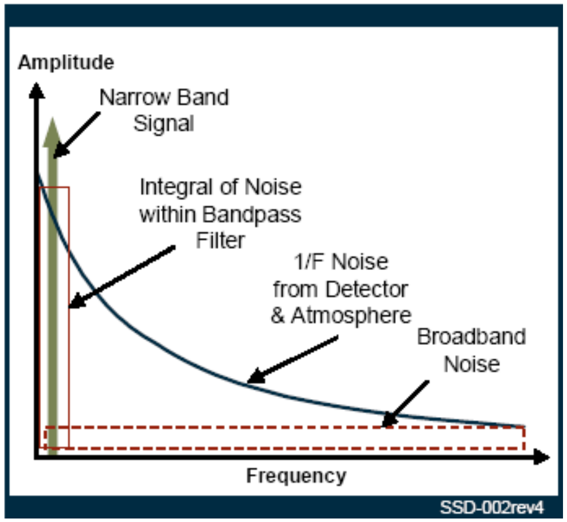
$$V_{ph.\ sens.\ det.} = [V_{sig}\sin(\omega_r t + \theta_{sig})]\,[V_L \sin(\omega_L t + \theta_{ref})]$$
$$= \tfrac{1}{2}V_{sig}V_L\cos([\omega_r - \omega_L]t + \theta_{sig} - \theta_{ref}) - \tfrac{1}{2}V_{sig}V_L\cos([\omega_r + \omega_L]t + \theta_{sig} + \theta_{ref})$$

- ***The PSD output is two AC signals, one at the difference frequency ($\omega_r - \omega_L$) and the other at the sum frequency ($\omega_r + \omega_L$).***
- ***If the PSD output is passed through a low pass filter, the AC signals are removed. What will be left? In the general case, nothing.***
- ***However, if ω_r equals ω_L, the difference frequency component will be a DC signal. In this case, the filtered PSD output will be:***

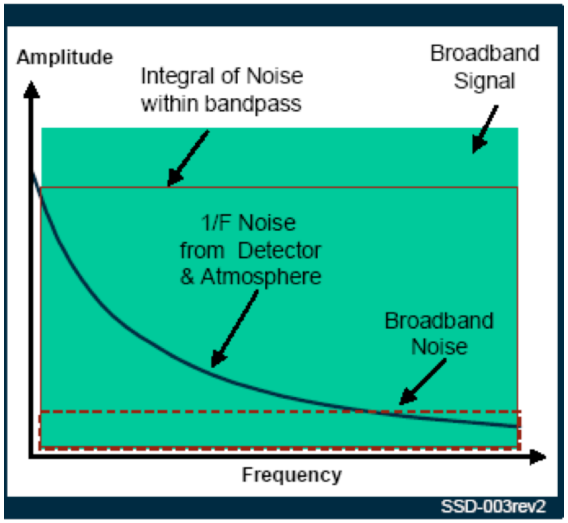
$$V_{psd} = \tfrac{1}{2}V_{sig}V_L\cos(\theta_{sig} - \theta_{ref})$$

[1] Stanford Research, Application Note #3

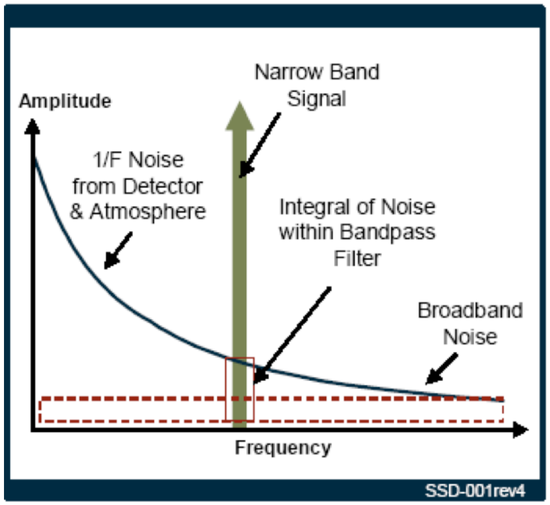
Laser Signal In Presence Of Large 1/F Noise.



CW at Baseband (No modulation)

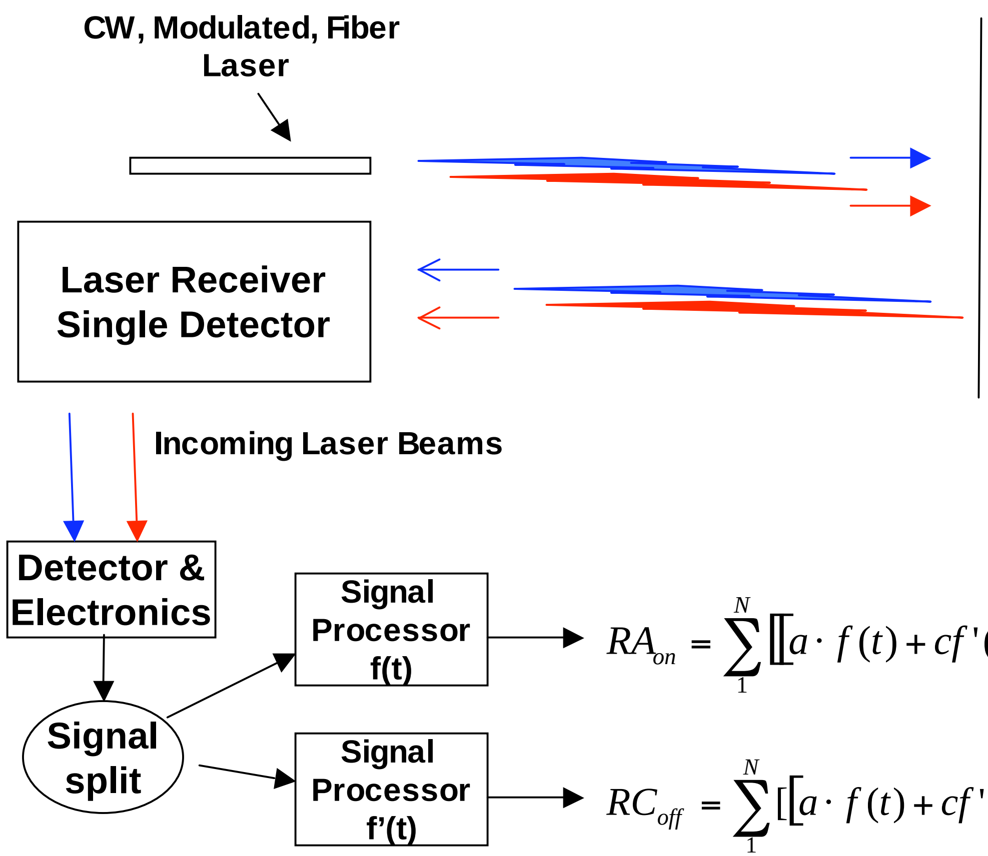


Pulsed (Broadband)



Modulated CW

Modulation And Signal Processing



$$L_{on}(t) = A \cdot f(t)$$
$$L_{off}(t) = C \cdot f'(t)$$

$\lambda_{on} \cong \lambda_{off}$

simultaneous

$$f(t) = \sin(\omega_1 \cdot t)$$
$$f'(t) = \sin(\omega_2 \cdot t)$$
$$f(t) = PN(k-m)$$
$$f'(t) = PN'(k-m)$$
$$PN(k-m) \bullet PN'(k-m) = 0 : Orthogonal$$

$$RA_{on} = \sum_{1}^{N} \left[\left[a \cdot f(t) + cf'(t)\right] \cdot X(t) + \delta_1(t)\right] \cdot f(t)$$

$$RC_{off} = \sum_{1}^{N} \left[\left[a \cdot f(t) + cf'(t)\right] \cdot X(t) + \delta_2(t)\right] \cdot f'(t)$$

X(t) ~ the modulation effects of speckle and air turbulence

δ_1 and δ_2 ~ the electronic noise terms generated in the photon to current conversion process; are considered small

Math of Lock-in Process When f(t)=sin(ωt)*

It is assumed that the integration time is long compared to: $\omega_1, \omega_2, (\omega_1 - \omega_2), and (\omega_1 + \omega_2)$

Define some terms which become small as the integration time increases:

$$\int_0^\tau \delta_1(t) \cdot \sin(\omega_1 \cdot t) \cdot dt \approx \delta_{11} \qquad a \cdot \int_0^\tau X(t) \cdot \sin(\omega_1 \cdot t) \cdot \sin(\omega_2 \cdot t) \cdot dt \approx \delta_{12}$$

$$c \cdot \int_0^\tau X(t) \cdot \sin(\omega_2 \cdot t) \cdot \sin(\omega_1 \cdot t) \cdot dt \approx \delta_{21} \qquad \int_0^\tau \delta_2(t) \cdot \sin(\omega_2 \cdot t) \cdot dt \approx \delta_{22}$$

Using $\sin^2(x) = \dfrac{1 - \cos(2x)}{2}$:

$$RA_{on} = \int_0^\tau \frac{a \cdot X(t) - a \cdot X(t) \cdot \cos(2 \cdot \omega_1 \cdot t)}{2} \cdot dt + \delta_{11} + \delta_{21}$$

$$RC_{off} = \int_0^\tau \frac{c \cdot X(t) - c \cdot X(t) \cdot \cos(2 \cdot \omega_2 \cdot t)}{2} \cdot dt + \delta_{22} + \delta_{12}$$

$$\frac{RA}{RC} = \frac{a \cdot \int_0^\tau \left[X(t) - X(t) \cdot \cos(2 \cdot \omega_1 \cdot t)\right] \cdot dt + \delta_{11} + \delta_{21}}{c \cdot \int_0^\tau \left[X(t) - X(t) \cdot \cos(2 \cdot \omega_2 \cdot t)\right] \cdot dt + \delta_{22} + \delta_{12}} \cong \frac{a}{c}$$

Atmospheric transmission from which optical depth of gas can be derived

The terms δ_{11}, δ_{21}, δ_{22}, and δ_{12} all get very small as the integration time increases.

Math of Correlation Process When f(t)=PN(k-m)

Ranging: R[m] is correlator peak

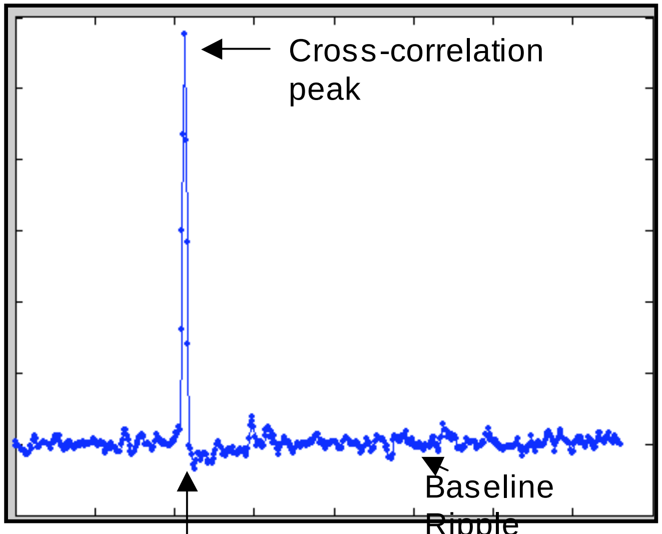
$$R[m] = \sum_{k=1}^{N} (\alpha PN[k-m] + \beta) \cdot X(t) * PN[k-m]$$

$$R[m] = \sum_{k=1}^{N} \alpha PN[k-m] \cdot X(t) * PN[k-m] + \sum_{k=1}^{N} \beta \cdot X(t) * PN[k-m]$$

$$R[m] = \alpha \cdot X(t) \sum_{k=1}^{N} PN[k-m] * PN[k-m] + \sum_{k=1}^{N} \beta \cdot X(t) * PN[k-m]$$

$$R[m] = \alpha \cdot X(t) * \delta(m-tr) + \sum_{k=1}^{N} \beta \cdot X(t) * PN[k-m]$$

β ~0 in photon counting mode



Correlation detection for ranging does not necessarily allow the effects of Speckle and Air Turbulence to be mitigated for a CW system.

LAS*: R[m] is correlator peak

$$R[m] = \alpha \cdot X(t) * \delta(m-tr) + \sum_{k=1}^{N} \beta \cdot X(t) * PN[k-m]$$

$$R'[m] = c \cdot X(t) * \delta(m-tr) + \sum_{k=1}^{N} \beta \cdot X(t) * PN'[k-m]$$

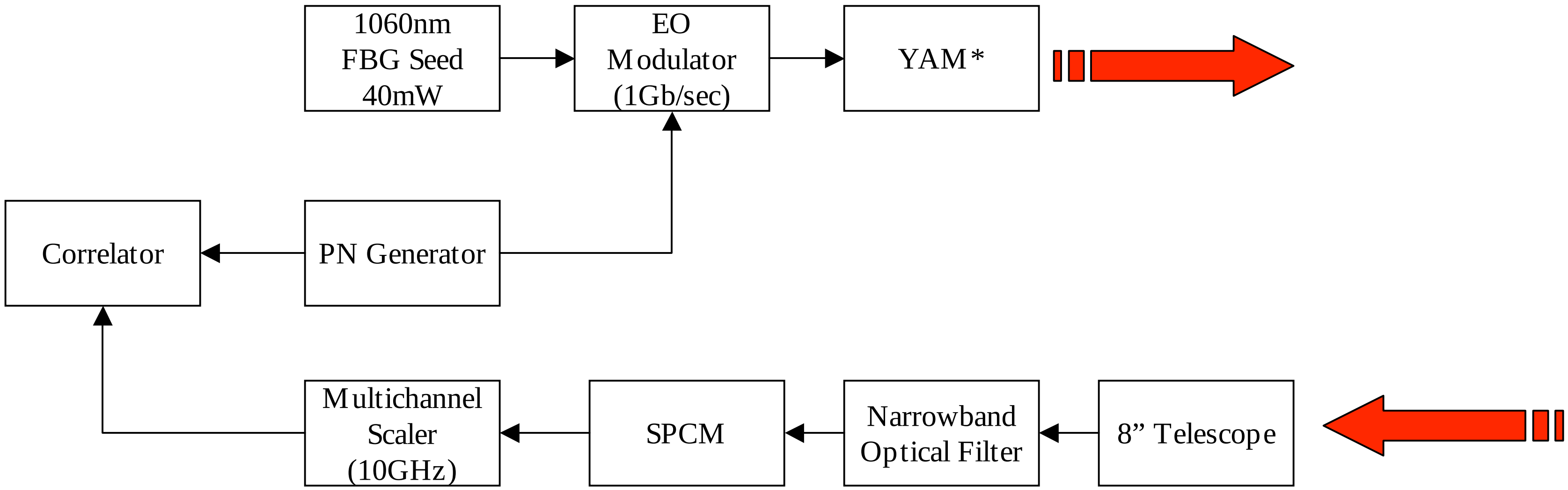
$$\frac{R(m)}{R'(m)} = \frac{\alpha * \delta(m-tr)}{c * \delta(m-tr)} \cong \frac{\alpha}{c}$$

Lock-in detection or Correlation detection allows the effects of Speckle and Air Turbulence to be mitigated in the ratio of the on-line / off-line for a CW system.

Status Of Development - Altimeter

Photon Counting PN Architecture

- Photon counting architecture
- Advantages
  - Orders of magnitude more sensitivity than analog
  - Simplified Electronics - No need for high bandwidth dewar design as with MCT APD
  - Simulation Completed & awaiting validation



*Only necessary for large standoff distance applications

Model Functional Block Diagram - Ranger

Transmitter
- Output Power
- Modulation Frequency
- Modulation Efficiency
- Transmitter Divergence
- Laser Noise Properties
- # bits

Atmosphere and Target Characteristics
- Target Albedo
- Scattering Solid Angle
- Path Length
- One Way Transmission
- Turbulence Noise
- Speckle Noise

Solar Background Noise
- Turn on or Off
- Angle of Sun

Receiver
- Receiver Area
- Receiver IFOV
- Receiver Effeciency

Optical Bandpass Filter
- Center Frequency
- Bandwidth

Detector
- Dark Count
- Quantum Efficiency
- Dead Time
- Bandwidth
- Timing Jitter

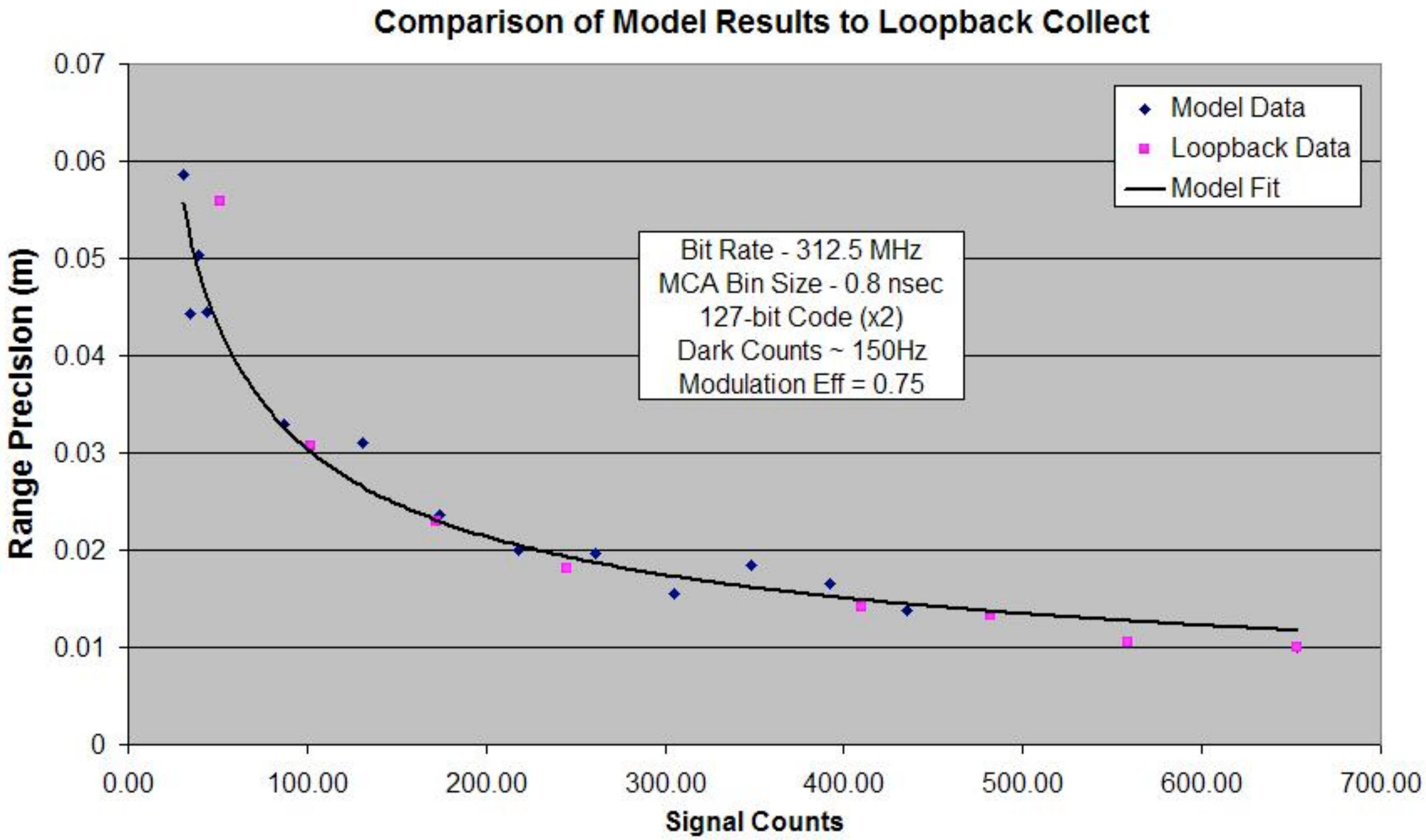
Multichannel Scalar
- Sample Rate
- Collection Period

Correlator Function
- Correlation Peak

Verification matrix

	ITEM	MEASUREMENT	ANALYSIS
Transmitter			
	Power	x	
	Modulation Bit Rate	x	
	Modulation Efficiency	x	
	Wavelength	x	
	Transmitter Divergence	**TBD**	
Target and Atmosphere Characteristics			
	Target Albedo	x	
	Scattering Solid Angle		x
	Path Length	x	
	One Way Transmission		x
Solar Background Noise			
	Day or Night	x	
Receiver			
	Receiver Area	x	
	Receiver IFOV		x
	Receiver Efficiency	x	
Optical bandpass Filter			
	Center Wavelength	x	
	Bandwidth	x	
	Transmission	x	
Detector			
	Dark Count Rate	x	
	Quantum Efficiency	x	
	Dead Time	x	
	Bandwidth	x	
	Timing Jitter	x	
Multi-Channel Scaler			
	Sample Rate	x	
	Collection Period	x	

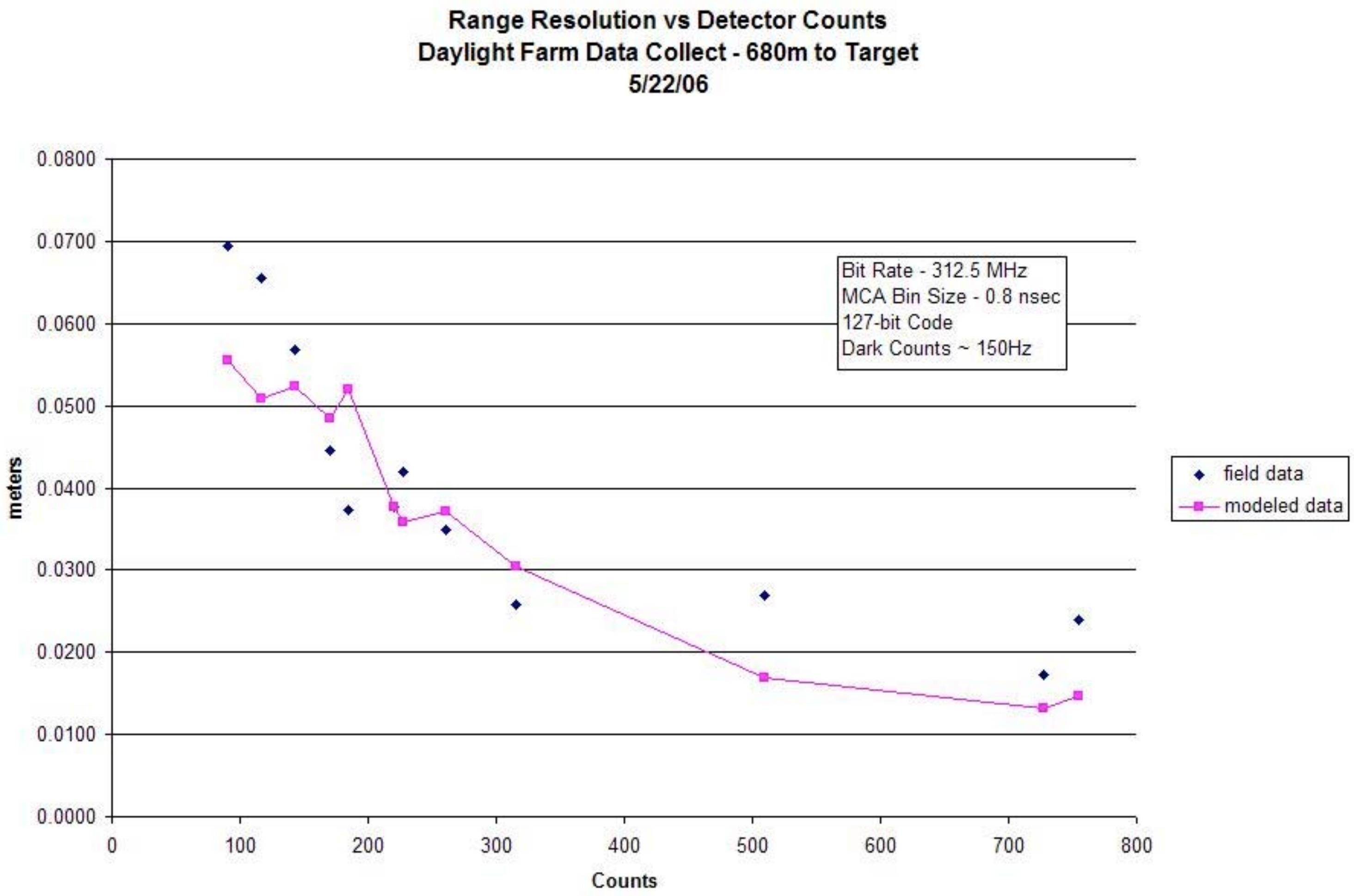
Ranger Sensor Test In Lab March 2006



Loopback fiber ~1000 m

Vertical resolution = 48 cm (bit width = 3.2 nsec)

Ranger Sensor Test In Field May 2006

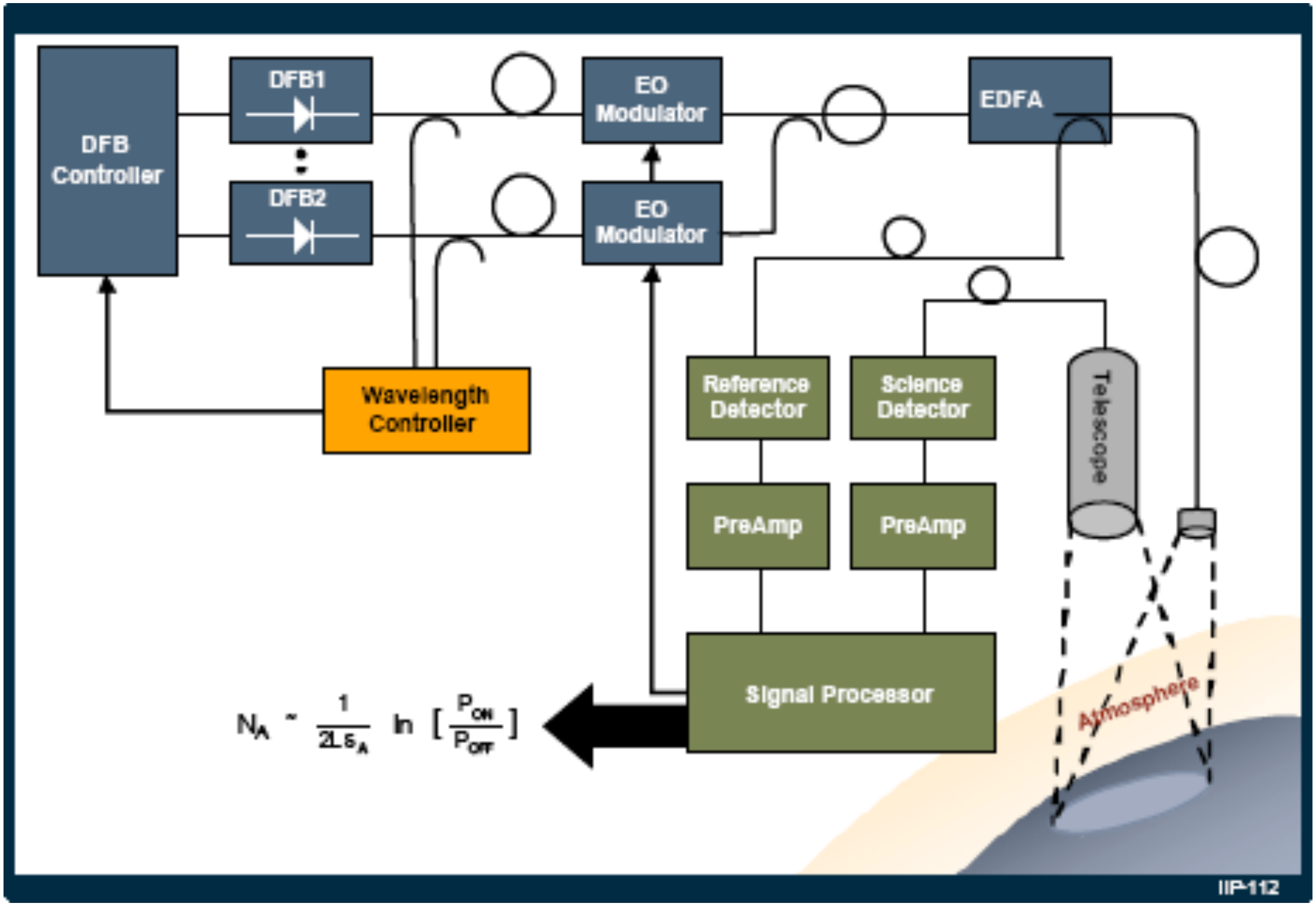


Ranger Status

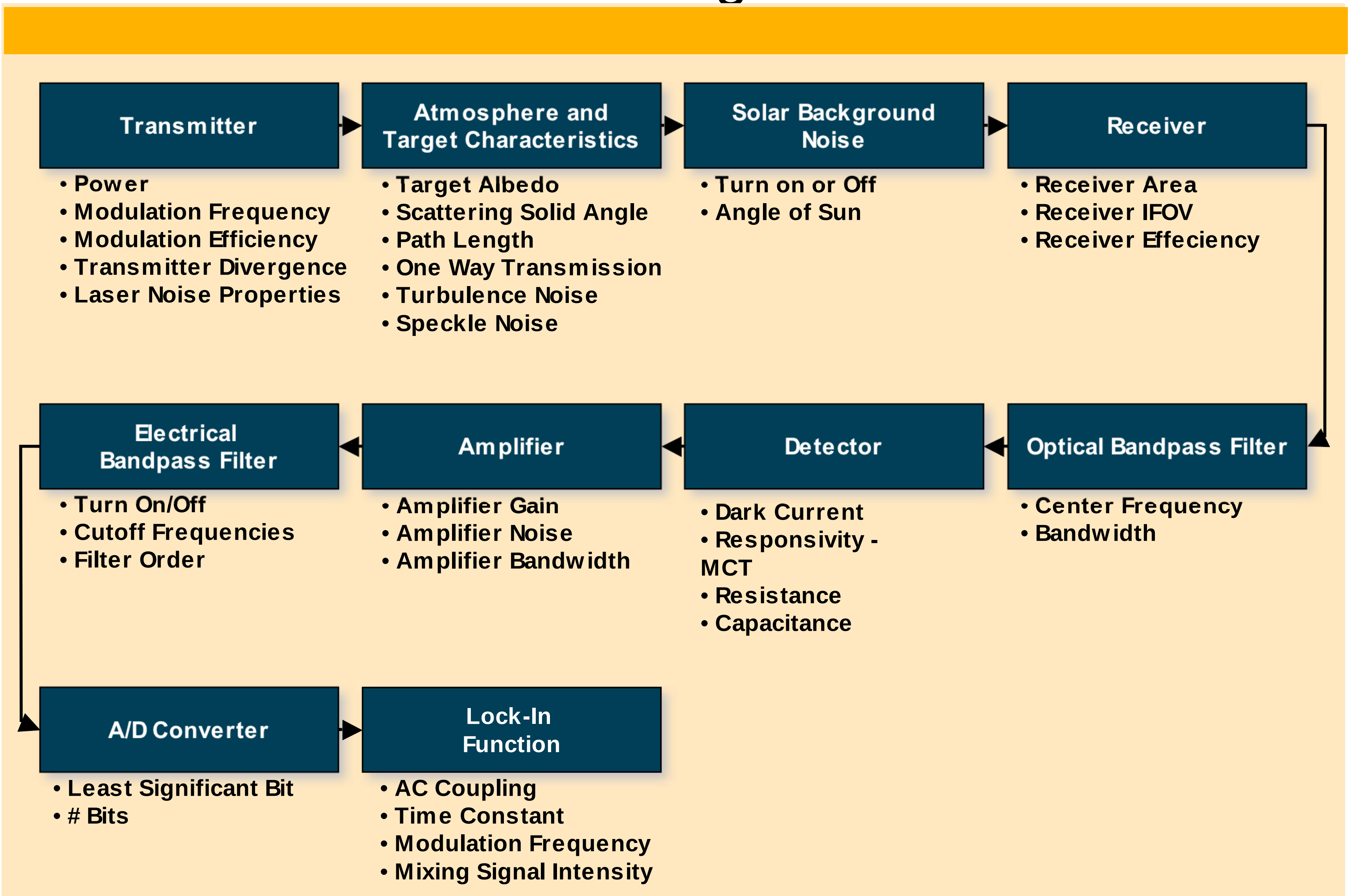
- **Physics-Based End-to-End Model Validation**
  - **Accounts for all instrumental effects.**
  - **Uses measured component data.**
  - **Validated using laboratory**
  - **Radiometry and signal-to-noise validated; therefore scaling to airborne is a low risk.**
- **End-to-End System Testing**
  - **EDU achieves required precision of 2 cm.**
- **Validation / Field Campaign**
  - **Engineering Checkout Mission – scheduled to fly June 2006.**

Status Of Development - LAS

Functional Diagram



Model Functional Block Diagram - LAS



Verification Matrix

	ITEM	MEASUREMENT	ANALYSIS
Transmitter			
	Power	x	
	Modulation Frequency	x	
	Modulation Efficiency	x	
	Transmitter Divergence	x	
	Laser Noise Properties	x	
Target and Atmosphere Characteristics			
	Target Albedo	x	
	Scattering Solid Angle		x
	Path Length	x	
	One Way Transmission		x
	Turbulence Noise		x
	Speckle Noise		x
Solar Background Noise			
	Day or Night	x	
Receiver			
	Receiver Area	x	
	Receiver IFOV	x	
	Receiver Efficiency	x	

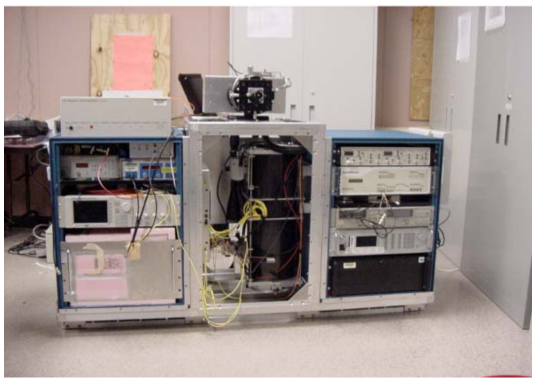
	ITEM	MEASUREMENT	ANALYSIS
Optical bandpass Filter			
	Center Wavelength	x	
	Bandwidth	x	
	Transmission	x	
Detector			
	Dark Current	x	
	Optical Gain	x	
	Responsivity		x
	Resistance	x	
	Capacitance	x	
Amplifier			
	Gain	x	
	Noise	x	
	Bandwidth	x	
Electrical Bandpass filter			
	Cutoff Frequencies	x	
	Filter Order		x
A/D Converter			
	Least Significant Bit	x	
	# Bits	x	
Lock-in function			
	AC coupling	x	
	Time constant	x	
	Modulation Frequency	x	

Modular Architecture Has Demonstrated Advantages

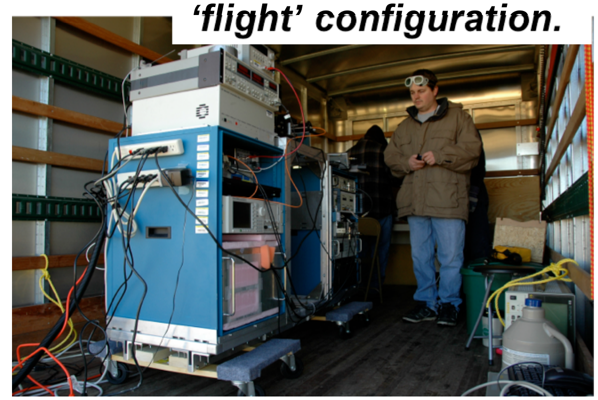
- the architecture is independent of the system wavelength
- supports multiple species simultaneously, as long as the transmitter has spectral bandwidth
- easily supports the N+1 redundancy

Total Column CO_2 LAS System (NIR) Field Testing

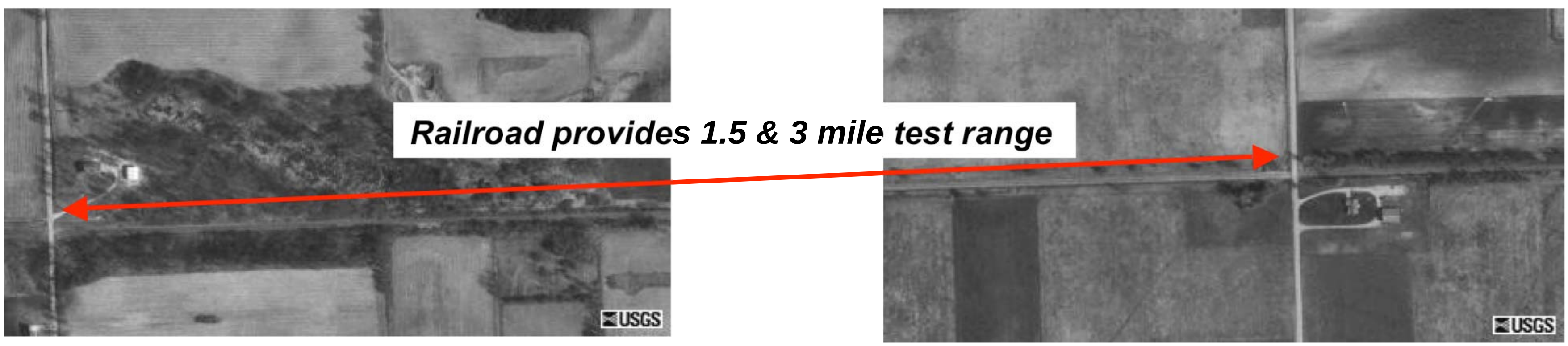
- Achieved SNR in excess of 1,000 at received power levels compatible with LEO orbit.
  - Continued range testing at 0.5, 1.5 and 3 miles using diffuse target.



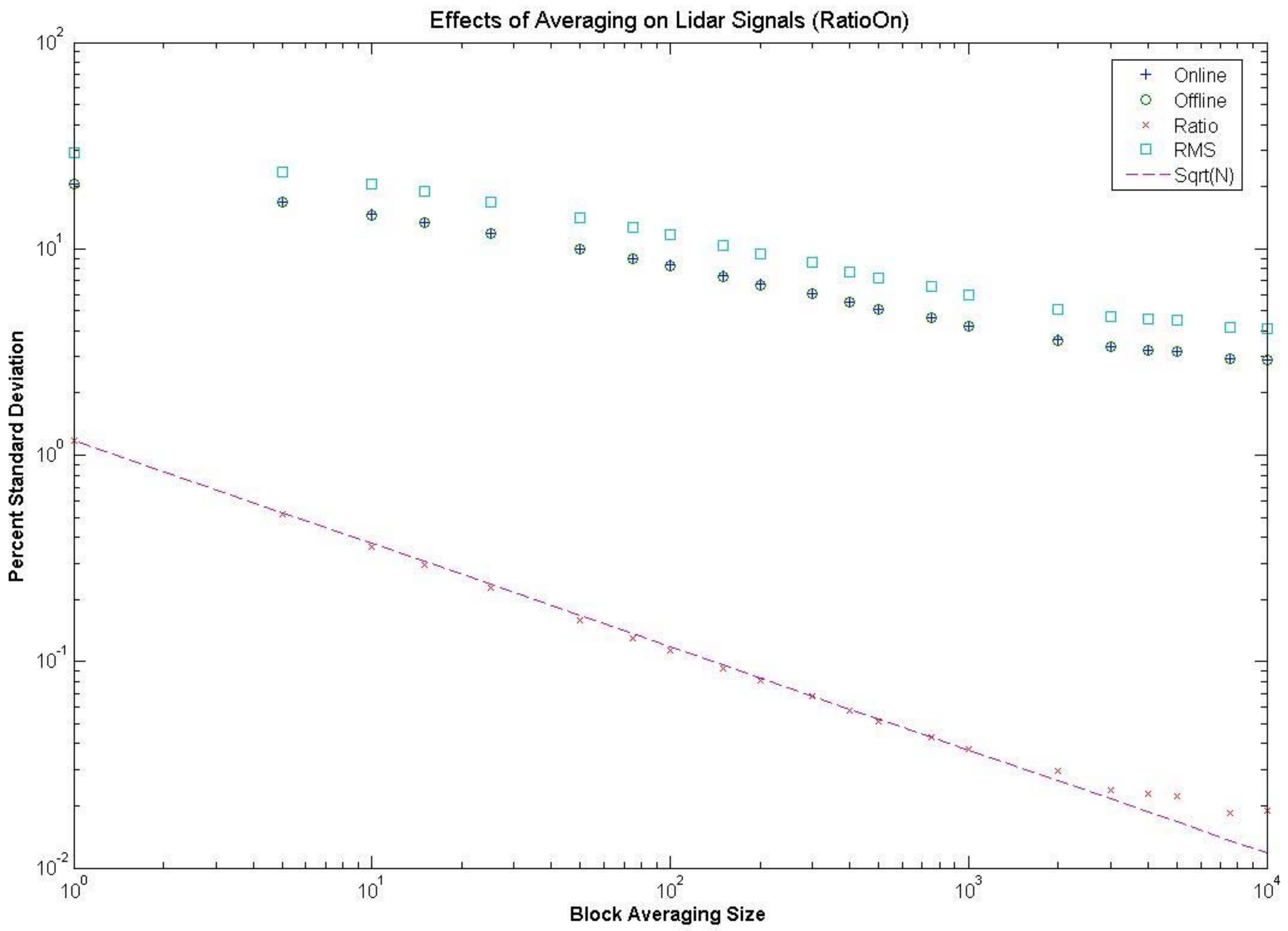
Tripod mounted telescope for terrestrial testing



Field testing done in 'flight' configuration.



Sensor Stability March 2006



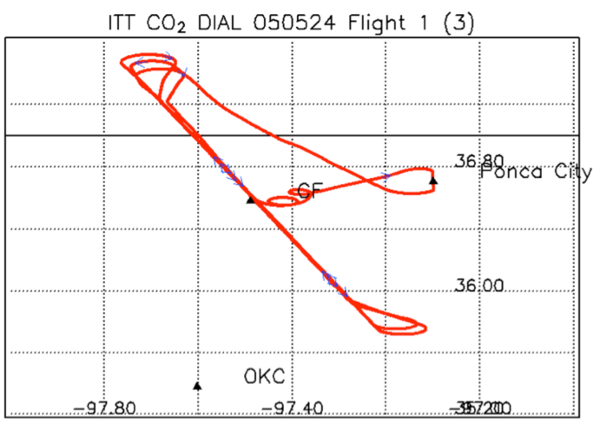
NOTE: 7200 sec data run

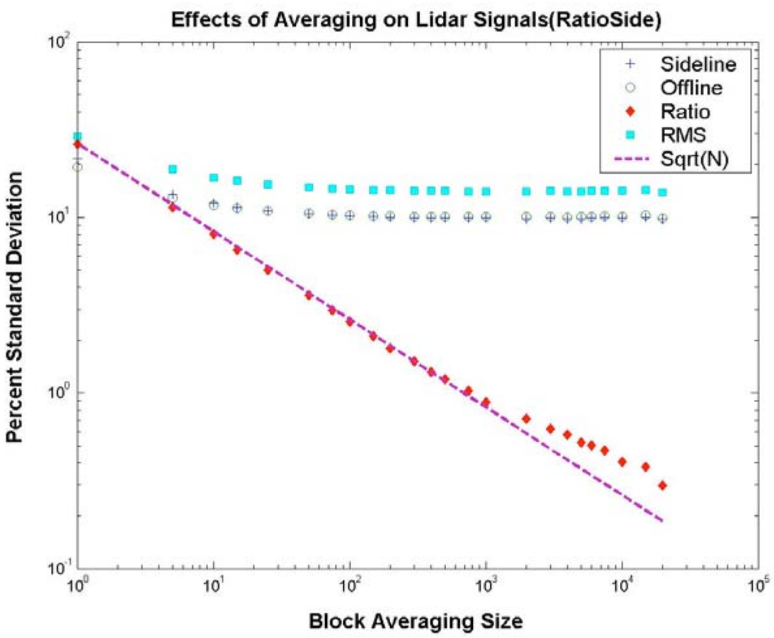
Total Column CO_2 LAS System (NIR) Airborne Testing

- Lear installation for airborne campaigns
- Two campaigns have been flown

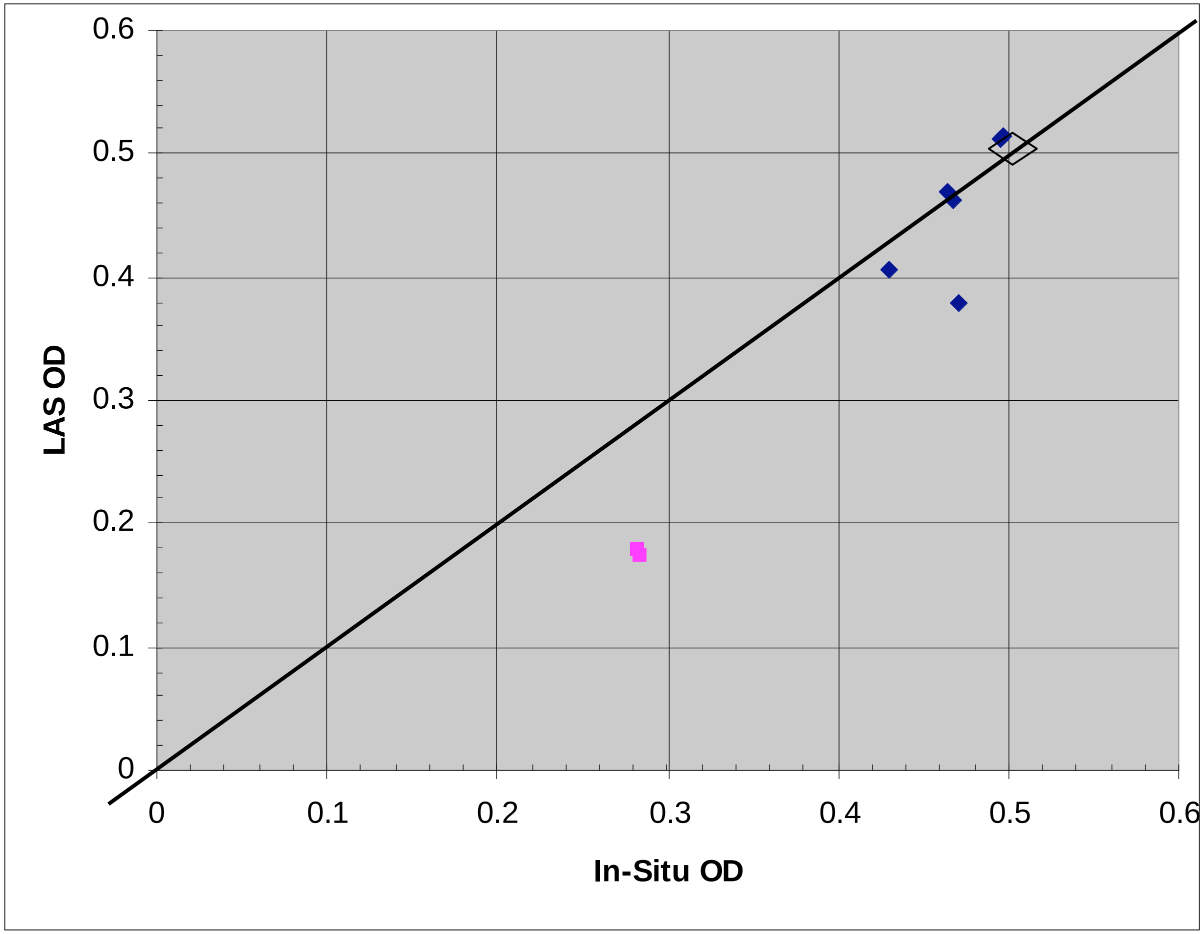
ITT Completes First Airborne Lidar Measurements of CO_2.

- Successful integration and operation of all systems - CO_2 lidar, pulsed laser altimeter, and in-situ CO_2 system with aircraft avionics, power, structure, and thermal systems.
- Obtained high-quality remote and in-situ data.
- Radiometric performance of CO_2 lidar instrument model matches observed data.
- Demonstrated High Signal-to-Noise and High Stability under adverse operational conditions.





Comparison of In Situ and DIAL 2-Way Optical Depths



- Side line measurement

CO_2 Lidar Status

- **Physics-Based End-to-End Model**
  - **Accounts for all instrumental effects.**
  - **Uses measured component data.**
  - **Validated using laboratory, long-range outdoor, and airborne studies.**
  - **Radiometry and signal-to-noise validated; therefore scaling to space is a low risk.**
- **Technology Readiness**
  - **Preliminary NEPP evaluation of qualification data for fiber laser based transmitter system is favorable.**
- **End-to-End System Testing**
  - **EDU routinely achieves required precision of 0.1%; with required long term stability.**
- **Validation / Field Campaign**
  - **Engineering Checkout Mission – Successful engineering checkout of all instrument and aircraft systems in December 2004 with several flights.**
  - **1st Science Mission – The ITT lidar flew (four flight missions) over DOE SGP site in May 2005. The ITT lidar matched the LaRC in-situ sensor to within 2.1%.**
  - **2nd Science Mission – Upgrades to EDU will permit completion of all objectives. EDU is scheduled to fly June 2006.**
- **Pursuit**
  - **Competition sensitive**

Risk Reduction And TRL Enhancement For Modulators and Fiber Amplifiers

Received Supplemental funding from NASA to accelerate fiber-based qualification work.

FY06 GSFC R&TD

Risk Reduction and TRL Enhancement for Fiber -based Laser/LIDAR Applications

PI: Melanie Ott, Code 562

Goddard Space Flight Center

Description and Objectives:

- Enable new class of reliable active measurement concepts based on fiber laser technology,
- Reduce the cost and complexity of fiber transmitters for space
- Enhance the technology readiness level of fiber transmitter components to a fully screened level for potential ESSP -class flight missions such as ACCLAIM.

Key challenge(s)/Innovation:

Prescreening components with physics -of-failure knowledge = proper packaging information to vendor for final space flight build – most failures are packaging related.

Researchers at NASA LaRC and NASA GSFC are aggressively investigating the use of fiber amplifier based systems for future missions but extensive test data does not exist for system operation in a spaceflight environment.

Approach:

- Validate flight candidates, commercial components;
  - 1.5 pm fiber amplifier during extended thermal -vacuum testing.
  - modulator thermal -vacuum performance and radiation tolerance.
- Provide baseline environmental data at 1.5 nm needed for future measurements.

Collaborators:

- Ed Browell , LaRC
- Michael Ciseweski , LaRC
- Mike Dobbs, ITT Industries

Milestones and Schedule:

- Procurement of modulator by LaRC -3/06
- Procurement of fiber amplifier from IPG by ITT - 3/06
- Testing of IPG unit in vacuum at LaRC 6/06 – 10/06.
- Thermal vacuum cycling of hermetic modulator at GSFC -7/06
- Radiation testing of hermetic modulators at GSFC -9-06
- Evaluation report drafted 11/06

Application / Mission:

- LIDAR configurations for the ESSP
- Earth Science, Planetary Exploration
- Entry -Descent -Landing (EDL) systems.
- Instrument Incubation program.

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